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Final Report

THE COMPUTER AIDED SYSTEM FOR
PLANNING EFFICIENT ROUTES

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Dear Kumares:  

Enclosed is the final report for the project titled "The Computer Aided System for Planning Efficient Routes: Implementation Study" (HPR-2063). It has been revised consistent with the comments proved by the reviewers, with which we entirely agree.

We appreciate the opportunity to conduct this research, and look forward to monitoring the further implementation of the CASPER route design environment.

Sincerely,

Jeff. R. Wright  
Professor
Final Report

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FOR PLANNING EFFICIENT ROUTES

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Professor
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Purdue University

Joint Highway Research Project

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Conducted in cooperation with the
Indiana Department of Transportation
and

Federal Highway Administration

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April 15, 1994
The Indiana Department of Transportation has sponsored the design and implementation of a decision support system for routing highway maintenance vehicles— the Computer Aided System for Planning Efficient Routes (CASPER). Designed for solving multiobjective route design problems, CASPER has been used by agency personnel to design routes for winter maintenance vehicles with significant results: cost savings of more than $9-million to the State of Indiana through more efficient use of materials, equipment, and personnel, while at the same time significant improvement in overall level of network and public service. CASPER integrates 1) an extensive spatial network database (GIS/CAD), 2) a models base consisting of multiobjective search heuristics and network algorithms, and 3) a template-driven and highly interactive user interface.
The Computer Aided System for Planning Efficient Routes

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Introduction

The focus of this work is the design and development of a computer aided system for assisting in the design of network service routes. The system integrates 1) spatial network data, 2) multiobjective heuristic optimization techniques, and 3) an interactive, user controlled graphical interface. This research was motivated by the need to design of winter snow and ice control service routes in Indiana, but the approach is generalizable to a wide variety of applications requiring service to the edges (road segments) of a network such as crack sealing, pothole repair, painting and striping, weed control, and scheduled inspection. The structure and function of this system are discussed, as well as an evaluation of its use to date by Indiana Department of Transportation maintenance engineers.

An important though often neglected factor in the development of strategies for the delivery of public services is the design of service routes. The importance of effective route design in the public sector relates not only to the cost of service provided, but also to a variety of intangible benefits such as quality and equity of service. While the importance of effective route design has been documented, as have the potential benefits resulting from route improvements, instances of implemented public sector routing systems are
rare. The magnitude and complexity of most public-sector routing problems have precluded the development of general-purpose, or even application-specific route design systems.

Regardless of the domain of application, routing problems may be classified in terms of the particular objectives and constraints inherent in a specific problem. Whereas private-sector routing problems are generally evaluated in economic terms—minimize cost, maximize net benefits, etc.—public sector vehicle routing problems are usually motivated by a desire to improve service or public welfare (Stricker 1970). Although there do exist complex constraints in routing problems faced by private organizations, the maximizing of benefits or the minimizing of costs is usually the ultimate and singular goal of most private sector routing problems. However, minimizing costs is not the only, nor is it usually the most important concern in public sector routing problems. Commonly, the objectives most important in the provision of public services relate to social well being, and thus may be difficult to quantify. Also, public sector problems tend to reflect multiple, frequently conflicting, and often simultaneous objectives (Stricker 1970, and Bodin et al. 1983).

Public sector service route design is generally more difficult than its private sector counterpart because the decision-making environment within which routing and the delivery of services take place is more complex. First, uncertainties may exist about the level of demand for services, or demand may experience significant, and often unpredictable changes over time. Second, important but intangible objectives, such as the public’s safety and satisfaction with the quality of service are difficult to measure, yet these objectives may be the most important when delivering public services. Third, even in cases where the system is well understood, and sufficiently good analytical procedures are available to model that system, public sector problems are more likely to be characterized by multiple and often conflicting objectives.

Because of the complexity and magnitude of the winter snow and ice control service route design problem faced by the State of Indiana, a research project was commissioned to design and develop a computer support environment within which existing service routes could be evaluated explicitly, and new ones developed. The result is a prototype spatial decision support system (SDSS) that has become known as CASPER, for the Computer Aided System for Planning Efficient Routes. The system has been used successfully in the re-design of service routes for approximately one third of the network maintained by the State of Indiana, and the remaining areas of the state are scheduled to be evaluated in the near future. Though the use of CASPER is still experimental, verifiable economic benefits to the State of Indiana have already reached several million dollars.

This research is presented in several sections. Following a description of the winter service route design problem faced by Indiana, as well as most northern states, the technical literature about route design methodologies relevant to this research is reviewed. Then the analytical framework of CASPER is presented including a discussion of 1) the spatial database requirements of the system, 2) the systems analytical model elements and atoms, and 3) system flow control and user responsibilities. The report concludes by document-
ing preliminary results from the use of CASPER by Indiana Department of Transportation (INDOT) maintenance engineers, and a prognosis for future use.

Snow Route Design in Indiana

Snow and ice control during the winter months in Indiana is, by several measures, a major operation (Indiana Department of Highways, 1985). The Indiana Department of Transportation must routinely maintain some 11,414 miles of roadway throughout the state. Because each traffic lane must receive service, this translates into more than 29,000 lane miles. The resources needed for this operation include nearly 1,500 trained personnel and some 1,200 maintenance vehicles. The cost is enormous—over $14 million was budgeted by the State of Indiana to support the operation during the 1990-91 winter season.

The overall goals of winter operations are to provide safe public driving surfaces, efficient use of maintenance vehicles and personnel, and effective use of materials. Each road segment in the state’s transportation network is routinely rated based on average daily traffic (ADT), and wintertime service requirements (measured by frequency of service, by type of service) are based on these ratings. During snow events, Class I roads (ADT greater than 5000) receive continuous service including plowing and the application of materials (salt, chemicals, and abrasives) as needed to keep the road surface bare; generally every two hours during an ongoing snow event. Class II roads (ADT between 1000 and 5000) receive continuous plowing and sufficient chemicals and abrasives to maintain bare wet pavement in the center portion of the road way; generally every three hours. Class III roads (ADT less than 1000) receive enough service to keep the routes passable, with chemical treatment only for hills, curves, and intersections; generally every four hours.

The design of service routes, including deadhead travel segments, are based significantly on this “time-to-service” parameter.

The INDOT snow and ice control policy is reflected in a set of pre-specified service routes, which generally do not change significantly from one snow season to the next (INDOT, 1985). These routes are administered out of field unit sites that also serve as depots for service vehicles and material storage. On the order of four units are administered out of INDOT subdistrict offices, which are in turn administered out of six district offices in the state. It is the responsibility of the subdistrict superintendent and the unit foreman to dispatch trucks for snow and ice control tasks along these predetermined routes. In most cases, route design is not an activity that needs to be conducted in real time, or even on a regular basis. Because the design of routes is a major determining factor of overall quality of service, and because the system is not flexible enough to accommodate changes during the winter season, it is important that the complexities and uncertainties associated with the operation be considered as explicitly as possible during route design and periodic re-evaluation of service routes.

Operational Objectives and Constraints

The quality of service is usually measured by the time-to-clear for each individual route. Better quality will be achieved when a shorter time is required to complete servic-
ing a route as more service can be provided per unit time. Yet shorter routes implies more routes will be needed to service a given partition of the network, which means more vehicles are needed. This conflicts with another goal of INDOT, that of minimizing operational costs. A typical service vehicle, including plow and spreading attachments, materials bins, and traction gear costs between $70,000 to $120,000.

Minimizing deadhead travel (travel over the network with no service being performed) is another important objective in the overall winter operation for two important reasons. First, and most important, the shorter the total deadhead travel on the network, the more time that a vehicle is providing service, and the more efficient is the service operation. Second, management is concerned with public reaction to the quality of service provided; traditionally, the most intense and frequent of all citizen complaints directed at winter operations relates directly to the amount of deadhead travel in a particular area.

Road class homogeneity is a third major factor in the effectiveness with which the snow and ice control operation is conducted. Resources are allocated to the network based on the historic importance of individual road segments. A lower class (say, Class II) road will be treated as a higher class (say, Class I) road, if this lower class road segment is included in a service route having higher class road segments. This class upgrading usually implies excessive resource usage, non-equity of service provided by class type, and most important, deterioration of overall service quality and increased cost. While many existing routes within the state include at least some mixing of class types, most operations engineers agree that reducing this ratio would improve effectiveness of operations.

**Overall Efficiency and Effectiveness of Route Design**

In designing an overall management strategy for snow and ice control, a number of difficult questions may be posed: What is the best set of routes for maintenance vehicles so as to maximize service level while keeping overall deadhead miles as low as possible? What characteristics of individual routes are most important in terms of overall safety of operation? What contingencies should be provided to compensate for the uncertainties of storm intensity? What characteristics should individual routes have in order to address the projected human resource (driver) availability or specific personnel capabilities? These questions and more should be considered in the design of an effective strategy for conducting winter road maintenance.

It is clear that the factors that determine the quality of service provided through the winter operation depend as much on intangible objectives as on tangible ones. Furthermore, from a modeling standpoint, a great number of very "low level" system components must be considered; factors such as differences in storm type and intensity, vehicle maneuverability, physical nuances of the network, differences in personnel skills. Because of these considerations, a practical approach to the design of a routing system such as the one produced through this research requires the ability to incorporate precise, but possibly not yet known system intricacies. The models developed through this research are thus properly perceived as mechanisms to aide the experienced and knowledgeable operations engineer, rather than dictating implementable solutions.
The route designer's challenge is to obtain, to the maximum extent possible, class homogeneity and service quality, while minimizing deadhead travel distance and the number of trucks and personnel needed. Management goals relative to route design are to form a collection of routes that are efficient in terms of the time to provide service, and compact in terms of the regions that they cover. An optimal collection of routes involves the definition of a travel sequence of road segments that minimizes the total time required to traverse the route when considering different travel speeds. The other perspective of an optimal collection of routes for the region being serviced involves determining a minimum number of routes for which the total travel time is minimized (Bodin et al, 1989).

**Previous Snow Route Design Research**

The problem of winter service route design as described above can be posed as a capacitated arc routing problem on a directed graph and has been proven NP-hard (Wang 1992). This suggests that the chances of finding a polynomial time algorithm is small. Consequently, the most successful implementations of the technology are likely to be based on heuristic rather than exact procedures. Nonetheless, limited work directed at solving this very difficult problem has been ongoing for several decades.

Stricker (1970) addresses the problem of urban snow removal using the Chinese Postman Problem (CPP) as the basic model. In his analysis of the snow plowing problem, he reveals shortcomings of the CPP model with respect to real world constraints such as the need for multiple plows and multiple lane roads. Cook and Alprin (1976) propose a closest street heuristic (or dynamic routing of spreader trucks) to address the urban snow and ice removal problem based on the assumption that there are no priorities associated with roads. Tucker and Clohan (1979) employ a simulation model to solve the same problem. The routing module (not really a model) in their simulation model provides a simple computer graph-based environment for users to design routes manually, and a preliminary way to predict the time needed to finish a particular route.

More recently, Haslam (1988) developed a seed node-based greedy “route growth heuristic” for extensive rural areas. Haslam's algorithm relies on users' experiences to pick these seed nodes judiciously. While preliminary results using this approach were shown to be promising—this work also used network data for the State of Indiana—, Haslam concluded that additional technologies will have to be incorporated into this approach before it can be used practically for most public-sector route design environments, particularly for more urban areas.

We conclude that the application of advanced analytical and numerical methods, and computer technologies to the problem of designing winter service routes is in its infancy. The ad-hoc methods mentioned above have not been thoroughly evaluated, and are not generalizable to other operations or applications. General routing algorithms from the fields of operations research and management sciences are too general or abstract to capture the intricacies of this problem domain. And commercial geographic information systems (GIS) software, while extremely useful for displaying problem solutions (route sets),
lacks the analytical tools necessary for finding efficient or effective route designs. Lastly, most of the work that has been discussed in the literature focuses on urban networks, not the rural areas that are the focus of the present research. A new framework for attacking this problem, and one that provides the foundation for the design and development of the CASPER route design prototype, is presented in the following section of this report.

A Framework for Multiobjective Route Design

Consider a maintenance engineer who is presented with the task of developing a new snow and ice control route design configuration for a portion of the intrastate highway system. The motivation for this assignment might be economic; for example the desire to reduce the size of the service fleet in this region to avoid having to replace an obsolete piece of equipment. Alternately, the motivation might have to do with improving service—new construction of road segments over the past several years may have resulted in a deterioration of service to a route that has subsequently grown in length. Still another motivation might have to do with human resources—personnel turnover may have resulted in the loss of very senior (and experienced) vehicle operators who were traditionally assigned to more complex and operationally difficult or more important routes. Whatever the motivation, the maintenance engineer wishes to at least review the existing route configuration in a systematic manner, and probably make modifications that will become part of future operations.

The ideal system for use by this individual should include several essential elements and be capable of a minimal functional level of performance. Necessary elements include: 1) sufficiently accurate and precise representation of the transportation network, including characteristics of each road segment as well as maneuver-specific node (intersection) information, 2) a model base containing appropriate data manipulation routines, and 3) a responsive visual interactive user interface having the appropriate level of user friendliness. Functionally, the system should facilitate the integration of model elements in a manner that is either meaningful to the decision maker in response to specific commands and instructions, or that is able to monitor the route design process, and provide non-procedural feedback about the quality of a given design. Furthermore, the system should be able to conform to the design "style" of the user. One user may wish to approach the design task by first looking at existing routes, and using a variety of route manipulation "tools" discover improvements, while another user may wish to begin the process by articulating a set of desirable characteristics for service routes, and have the system automatically generate some good starting configurations prior to "hands on" manipulation towards improvement.

These criteria guided the design and development of the prototype network decision support system resulting from this research. Like its namesake "CASPER: the Friendly Ghost," this route design system is a bit intimidating at first; particularly for individuals not familiar with high-end computer technology. But after becoming more familiar with
the system, users are able to understand that CASPER is not a threat, but a great help in addressing the very complex problems associated with route design.

Figure 1 presents the general framework of the CASPER route design system. A user friendly interface acts as the communication media between users and CASPER. With the assistance of this interface, users can manipulate data, design routes, and control the behavior of CASPER, while CASPER solicits appropriate user inputs and display intermediate results graphically to users. The spatial network database can be accessed and modified by users via a data filtering module. Users can elect to "toggle" automatic route design modules, invoke CAD-type operators to change route configurations manually, or a combination of both. The central automatic design module will find and launch the appropriate models/tools in the model base to meet user's requests. The connection between route design modules and the data filtering module provides users with a way of manipulating data during the route design procedures. Or a direct connection from the database to the routing model base allows tools resident in this model base to gather information without the intermediate data filtering module as this operation is user independent. With this as a general description of CASPER, the structure and function of the data and models base components of the system are discussed in more detail, below.

**Database Development**

For the application of vehicle routing over the state highway network, a complete spatial description of the network is used by CASPER. This description must include all major intersections in each district, adjacency information that indicates which intersections are joined directly by which roads, and the lengths of each of these roads. Planning for snow and ice control requires additional information, such as the average daily traffic,
the number of lanes of every roadway, and more complete descriptions of intersections, including features such as turn lanes or traffic control devices.

A major activity in support of this work has been to explore available digital map data sources, and to find the best methods to convert these data to a usable network representation. The most promising format for this application is a vector format in which roadways are represented as polylines; a set of short segments connecting two intersections. The source for vector data thus far has been the U.S. Geological Survey Digital Line Graph (DLG) format. Roadway information is available for the entire State of Indiana, and all other states of the U.S. at 1:100,000 scale.

The use of these data for route design and analysis is hindered by two distinct factors. First, the DLG data set includes considerably more data than are needed for route design. Second the classifications and characteristics attributes used by USGS may not be satisfactory for a given route design problem. For example, USGS does not classify intersection nodes as being inappropriate for maneuvering a snow removal vehicle through a U-turn. Existing map representations of the highway network could be used as a data source for optimization, although the complexity of these data could prove difficult in the definition of solution methods. Only with intelligent and efficient filtering and reclassification are these data a useful resource in practical route design and network logistics applications.

Prior to the use of the CASPER prototype, a comprehensive database containing this information was required, and has since been developed for the entire State of Indiana. An efficient and “smart” data filtering/classification module was developed and integrated into CASPER. The interactive DLG-3 data filter consists of three separate, but related functions: 1) input of the original DLG-3 data files, 2) interactive reclassification of road and node (intersection) objects, and 3) output of reclassified data files in DLG-3 format. The basic structure of these procedures is illustrated in Figure 2. Local transportation network experts (field engineers in INDOT organization; maintenance engineers in our figure) are the key components in this data filter/classification process. The maintenance engineers are usually those individuals who are responsible for snow route design within each district, and who have extensive knowledge and experience within his/her area of responsibility. A user-friendly interface was developed to help users to provide this essential information. The user develops a “template” representation of the node (intersection) or arc (road segment) that s/he desires to reclassify, then imposes that template on the target database graphics objects.

Figure 3 illustrates the logic of this data filtering/classification process. Users may either select existing road or node objects, or elect to add new nodes into the database. If node or road objects are selected, a template dialogue box is available for users to specify the characteristics of the selected objects (examples of these dialogue boxes are shown in Figure 2). For example, the user may declare the selected road objects as a Class I road having two lanes, a travel speed while servicing of 15 miles/hour, and a deadhead speed of 30 miles/hours. A similar procedure is used to classify node objects (turn maneuvers, etc.). The process continues iteratively until the entire network has been reclassified, or
verified. A preliminary Computer Aided Design (CAD) capability is included in CASPER to allow user to create new nodes in the database, such as the crossovers locations along interstate highways, intermediate salt storage facilities, or other relevant objects that may not be georeferenced in the DLG data set as acquired from the U.S. Geological Survey. Upon completion of the data filtering/reclassification process for a unit or subdistrict, other maintenance engineers who are familiar with other portions of the network would repeat the process for their areas of responsibility. Modifications to these parameters of the database may also be made during route design.

**Model Elements and Integration**

In order to assist users in designing efficient routes and to accommodate different users decision making styles, a local improvement heuristic-driven route design model has been developed. The rationale behind local improvement is that given a current solution,
an improved solution may lie within the neighborhood of that solution. At the termination of systematic search procedure, the best solution found is considered the optimal solution. A major problem in the design of the local improvement heuristic to avoid the circumstance where a search is trapped in a local optimum. The search strategy adapted for use in CASPER is the Tabu Search first articulated by Glover (1990). Details of that algorithm are presented in Appendix A. The interested reader is referred to Wang (1992) for a more detail discussion of the application of Glover’s Tabu Search procedure to problems of snow route design.

Because of the complexity and intricacies in winter service route design, an effective modeling environment within this domain must provide enough freedom for users to design their own search strategies and to override system recommendations at any time. By specifying the trade-off among the objectives and allowing modification of the local improvement evaluation criteria, users need to be able to emphasize different objectives in different situations and determine more precisely, the model’s searching range and direction. Users must also be able to override the routes suggested by the system and modify routes manually in order to address specific, and unanticipated considerations.

The structure of the local improvement route design model within CASPER is illustrated in Figure 4. The first step in the route design process is to specify the target routing area (the subnetwork and depot for which routes are to be designed). Currently, only a sin-
A graph consisting of nodes and directed arcs is then be created automatically based on the area selected. Alternately, the user might elect to use the existing set of routes for a particular area as a feasible starting point. The remainder of this discussion assumes that the user has elected to design a completely new set of service routes.

An empirical analysis is performed to estimate the number of vehicles needed and to determine the associated class of each route. An ad-hoc heuristic procedure for generating such an initial route is presented in Wang (1992). This initial route set becomes the "current route set" automatically as it is generated. The local improvement procedure can then be invoked by the users in an attempt to find an improved route. Two possible outcomes may result from triggering the improvement procedure: 1) an improved solution is found, or 2) an improved solution is not found after a user specified number of iterations. If the user is satisfied with the outcome, the procedure simply stops and outputs the best routes found. Otherwise, users may provide additional information (the specific mechanism for providing this input is discussed in detail later) reflecting personal preferences or different
ideas, and then trigger the local improvement procedure again. These procedures (local improvement and users input) will be repeated until a satisfactory solution is found.

By iteratively evaluating the current route, users are able to "direct" and "control" the local improvement search direction by changing policy settings, modifying routes manually, or reclassifying data. It is assumed that each new (improved) solution will stimulate thoughts and ideas from users regarding the quality of routes. Experienced users are able to identify the "good" and "bad" parts of current routes, and to guide the system accordingly. At any point in this process, a current route may be saved and "marked" for later consideration and comparison with other route sets.

The policy specification involves the setting of weighted parameters that are associated with the objectives discussed previously, and the specification of other criteria used by the improvement heuristics. The following parameters may be set or modified and manipulated by the user to control the design policy:

- The values of the weighted parameters associated with design objectives.
- The maximum number of search attempts to find an improved solution under the current policy.
- The class upgrade limitation. As indicated before, a class upgrade (e.g., from Class II to Class I) will take place when a lower class route (a Class II route) accommodates a higher class road (a Class I road). This limitation specifies whether class upgrading is allowed and to what extent it is allowed. For example, users can specify that only the upgrade to the next higher class is allowed. Under this restriction, a Class III route can be upgraded to Class II but not to Class I.
- Routes that are not allowed to be modified. Occasionally, users are satisfied with some of the routes and do not desire further modifications. In this case, users can declare these routes to be frozen and no additional modification is allowed (automatically). Thus, no arc will be swapped into or out of these "good" routes.

In addition to modifying the policy setting to direct the search, users may want to modify routes manually to address important intangible concerns. These concerns, such as the locations of sharp curves, steep slopes, poorly designed intersections, important residence areas, and individual driver's experiences, are usually missing from the available data and their importance, impact, and trade-off with the other objectives are usually difficult to measure accurately. It is likely that these subjective issues are most difficult to address adequately in a predefined model and probably will not be raised and identified until users have a chance to evaluate routes. For example, users may want to assign manually a Class II road with steep slopes to a Class I route. By doing this, a certain degree of class continuity is sacrificed in exchange for a higher degree of public safety. It is infeasible to be able to anticipate all such circumstances, or to generalize them among different service areas or different personnel experiences.

Another option is provided by allowing users to go back to the database and modify road and node attributes during route designing procedures. Occasionally, it is desirable for users to modify data attributes after evaluating current routes so that these changes will be accommodated in the next improvement iteration. For example, users may want to de-
clare some new points as (no) turn-around locations or to modify the traveling speed or the class for some road objects. Severe drifting conditions on a particular road segment may best be handled by different travel speeds in different directions on the same road. This does not mean that errors exist in the data, but rather allows a mechanism by which users can change some of his/her previous subjective judgments.

The total number of snow and ice removal vehicles required to service a specific sub-network is the major factor in determining overall costs and thus it is usually desirable to minimize the number of vehicles used to provide an adequate level of service and without sacrificing public safety significantly. In some instances, it may become clear that the total number of required vehicles could be reduced. For example, three 1.2 hour Class I routes are likely to be replaced by two 1.8 hour long routes. When such a situation occurs, users can select a route to be “deleted” and each arc served by that route will automatically be assigned to the appropriate route(s) based on the current policy setting.

By coupling the above tools, and with the flexibility provided by CASPER, users are able to direct the route improvement search direction, and interact with the system at any time. Different users’ decision making styles and other intangible concerns may be accommodated in this manner. For example, for some users the highest priority may be the objective of reducing deadhead distance. After achieving a small deadhead distance, users may put more emphasis on the objective of class continuity in an attempt to balance these two objectives. At the same time, the capability of allowing users to override and modify the outcome of local improvement procedures and to reclassify data offer a greater degree of flexibility for users to reflect the real world situations and personal preferences.

Test Results

Following initial prototype system development, several unit sites were selected for testing the route design capability of CASPER. The districts involved in this evaluation stage were the Crawfordsville District and the Greenfield District. The Carbondale Unit was selected as a representative service unit for the Crawfordsville District, and route design was conducted by Mr. Michael A. Smith; former field engineer and the individual who designed the existing snow routes. In Greenfield District, two adjacent units, the Tipton Unit and the Kokomo Unit were selected, with designs being completed by Mr. Karl Kleinkort (the field engineer), Mr. Joe Olson (the subdistrict manager), and the foreman from each unit.

Crawfordsville District

Area Characteristics and Objectives—Currently, Crawfordsville District is suffering the shortage of human resources (drivers) and the available vehicles are just enough to cover all existing routes. When some vehicles break down during the winter season, a frequent occurrence, it causes serious operational and administrative problems, and service levels may be deteriorated significantly. Therefore, the major goal for service route design
### TABLE 1. Existing Routes For Carbondale Unit
Total Value: 148.1

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<td>54.2</td>
<td>32.1</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>3.2</td>
<td>2.1</td>
<td>0.0</td>
<td>5.0</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>2.5</td>
<td>5.6</td>
<td>0.0</td>
<td>5.6</td>
</tr>
</tbody>
</table>
within this district is to reduce the number of routes without sacrificing service level or public safety significantly.

**Carbondale Unit Results**—The comparisons of current routes and the routes design using CASPER is shown in Table 1 and Table 2. Both of these tables contain data measuring the quality of two different route configurations for the Carbondale service unit. Table 1 presents a solution requiring 7 individual routes, each represented as a row. The entries in the second column is the class associated with each route. The entries in column 3 - 5 for a given route indicate a penalty attainment level measured for that route for three important service criteria: service time, deadhead miles, and class continuity, respectively. The rightmost column is the penalty “score” as mapped through a penalty function established by the user, with the overall penalty score for that particular set of routes indicated as “Total value.” The smaller that number, the better the route configuration. For example, the 7-route solution shown in Table 1 has a total penalty value of 148.1.

Table 2 presents another solution, and one that is better than the previous solution in two important ways. First, the overall level of service is better (the total penalty score is only 51.9), and second, the solution requires one fewer route; 6 rather than 7. Given that each route requires capital equipment, the solution presented in Table 2 is not only better, but less expensive than that presented in Table 1. The first solution is the route design used by INDOT for the Carbondale Unit during the 1991-92 and all previous winter seasons. The second is one designed by INDOT maintenance personnel using CASPER, and that was instituted for the 1992-93 and subsequent seasons.

**Greenfield District**

**Area Characteristics And Objectives**—Though adjacent, the Greenfield District has very different characteristics from those of the Crawfordsville District. This district (at least, Tipton Subdistrict) does not suffer the shortage of vehicles and human resources. Furthermore, additional vehicles are available for next winter season. Because of ample availability of operating resources, the goal of this district is to utilize all of the available resources in an optimal manner in order to achieve the maximal service level. Also, some routes have been found to be practically infeasible during last year’s practices. Another goal of this district is to improve these infeasible routes as well.

**Tipton Unit Results**—Table 3 and Table 4 show the current routes and the routes produced with the aid of CASPER for the Tipton Unit, respectively. At the first glance, it is surprising to note that the additional vehicle does not seem to improve service level significantly—total penalty reduction from 131.7 to 112.4. But in reality, at least one of the existing routes is infeasible based on INDOT’s specified service policy; a three hour Cass II route with a small deadhead distance, should be considered a “near-perfect” route according to INDOT’s policies. However, this route becomes impossible to maintain when there is wind blowing and drifting the snow during a winter storm, which is the normal experience in this area. Under such weather conditions, when a truck finishes the south part of this route, the snow accumulated on the north part becomes impossible to service, often
### TABLE 3. Existing Routes For The Tipton Unit
**Total Value: 137.3**

<table>
<thead>
<tr>
<th>Route (1)</th>
<th>Route class (2)</th>
<th>Time (hrs.) (3)</th>
<th>Deadhead (4)</th>
<th>Class cont (5)</th>
<th>Value (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.8</td>
<td>8.1</td>
<td>0.0</td>
<td>8.1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1.8</td>
<td>8.1</td>
<td>0.0</td>
<td>8.1</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3.0</td>
<td>2.4</td>
<td>0.0</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2.3</td>
<td>0.0</td>
<td>57.2</td>
<td>56.2</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2.5</td>
<td>10.3</td>
<td>44.6</td>
<td>33.6</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2.5</td>
<td>22.6</td>
<td>0.0</td>
<td>22.6</td>
</tr>
</tbody>
</table>

### TABLE 4. Routes Design Using CASPER For The Tipton Unit
**Total Value: 112.4**

<table>
<thead>
<tr>
<th>Route (1)</th>
<th>Route class (2)</th>
<th>Time (hrs.) (3)</th>
<th>Deadhead (4)</th>
<th>Class cont (5)</th>
<th>Value (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.9</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1.8</td>
<td>8.1</td>
<td>0.0</td>
<td>8.1</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2.0</td>
<td>18.4</td>
<td>0.0</td>
<td>27.6</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2.5</td>
<td>22.6</td>
<td>0.0</td>
<td>22.6</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2.0</td>
<td>1.3</td>
<td>0.0</td>
<td>1.3</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2.5</td>
<td>10.3</td>
<td>44.6</td>
<td>33.6</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1.5</td>
<td>0.0</td>
<td>64.8</td>
<td>19.0</td>
</tr>
</tbody>
</table>
requiring road closure. This emphasizes the importance of having human (expert) involvement in service route design. Only the experienced domain experts are able to recognize such fine points of route design and to address them appropriately. In this test, CASPER successfully helps users to correct an “infeasible” route, to accommodate users’ request of having a seven-route solution, and to comfort the users’ desire of totally controlling CASPER’s route improvement behavior.

Kokomo Unit Results—Table 5 and Table 6 compare the existing routes and the routes designed by CASPER for the Kokomo service unit. Unlike the Tipton Unit, no additional vehicle is available for this area. The major goal is to maximize the service level by using all of available vehicles with a minimal operational cost. According to the statistics shown on these tables, the service level is improved significantly—improvement from 446.47 to 53.6 using CASPER.

Another interesting observation is that all current used routes are Class I routes and one out of the six CASPER produced routes is a Class II route. This difference indicates that the CASPER produced routes use resources (sand and abrasive materials) in a more effective manner; recall that unnecessary materials will be applied to the lower class roads when they are integrated to a higher class route. Again, the use of CASPER does manage to improve the overall service level while allowing resources to be utilized more efficiently. The next section presents results from the preliminary design of routes for 40% of the states service units using CASPER.

Implementation and Results

Before INDOT could begin designing snow routes for the state a design policy and protocol for using the prototype software had to be established. CASPER was originally conceived of to design routes with a flexible user definable policy. That is, CASPER designs routes based on several objectives that the user has the ability to set relative levels of importance for. Specifically, the amount of deadhead mileage, adherence to class continuity, and time limit for each class of route can each be given a value on a scale of zero to 100 that defines how important that objective is relative to the other two. There are several other user definable parameters that are explained in Appendix A: Implementation Guide for CASPER.

A meeting was held prior to the beginning of the route design process for the state where it was decided that it would be best to design the state’s first set of routes with a uniform and fixed policy. This three part policy is commonly referred to as the CASPER penalty function.

Casper Penalty Function

The Casper penalty function is used by the route designer to help evaluate the goodness of any given set of routes. After several discussions with INDOT personnel and testing with the Crawfordsville District the following criteria were used to determine the penalty score for all routes designed by INDOT. Any given route’s penalty score is com-
### TABLE 5. Exiting Routes For The Kokomo Unit
**Total Value: 446.47**

<table>
<thead>
<tr>
<th>Route (1)</th>
<th>Route class (2)</th>
<th>Time (hrs.) (3)</th>
<th>Deadhead (4)</th>
<th>Class cont (5)</th>
<th>Value (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2.0</td>
<td>15.0</td>
<td>0.0</td>
<td>15.0</td>
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<tr>
<td>2</td>
<td>1</td>
<td>2.1</td>
<td>1.5</td>
<td>46.4</td>
<td>23.5</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2.6</td>
<td>9.5</td>
<td>54.3</td>
<td>318.9</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.9</td>
<td>6.5</td>
<td>0.0</td>
<td>6.5</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2.4</td>
<td>17.3</td>
<td>0.0</td>
<td>82.6</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### TABLE 6. Routes Designed By CASPER For The Kokomo Unit
**Total Value: 53.6**

<table>
<thead>
<tr>
<th>Route (1)</th>
<th>Route class (2)</th>
<th>Time (hrs.) (3)</th>
<th>Deadhead (4)</th>
<th>Class cont (5)</th>
<th>Value (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.8</td>
<td>0.0</td>
<td>25.4</td>
<td>7.9</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2.0</td>
<td>6.5</td>
<td>0.0</td>
<td>6.6</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2.1</td>
<td>10.4</td>
<td>0.0</td>
<td>11.5</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2.6</td>
<td>1.5</td>
<td>0.0</td>
<td>1.5</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1.8</td>
<td>0.4</td>
<td>0.0</td>
<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1.9</td>
<td>15.9</td>
<td>0.0</td>
<td>25.3</td>
</tr>
</tbody>
</table>
prised of three contributing factors: total service time, deadhead distance, and class continuity.

**Total Service Time**

Class I routes have a target service time of two hours and Class II & III routes have a target service time of three hours. Service times are based on a deadhead speed of 40 m.p.h. and a speed of 20 m.p.h. For Class I routes a penalty value of zero is assessed for routes that have a service time between 90 and 120 minutes, corresponding to the ideal service time window. For Class II & III routes the ideal service time window with zero penalty value is between 150 and 165 minutes. For any Class route if the service time is either below or above the ideal service time window, then a cubic function is used to determine the penalty value based on the number of minutes the route is below or above the lower or upper bound of the window. For example if a Class I route has a service time of 85 minutes, then the total service time penalty value contribution to the route’s total penalty score would be $5^3 = 125$ points, for the 5 minutes the route was below the lower bound of the ideal service time window (90 minutes).

**Deadhead Distance**

For any Class route, one deadhead mile equals one penalty point for each deadhead mile in the route.

**Class Continuity**

For any Class route, the number of off-class miles in the route divided by three equals the number of penalty points for the route. Three was chosen to cause deadhead mileage to be roughly three times more important than class continuity or the number of off-class miles in a route.

This penalty structure causes total service time to be the most important consideration when designing routes. If a route is more than 10 minutes above or below the ideal service time window then its penalty score will be at least 1000 and deadhead or class continuity won’t matter much with regard to the penalty score. It should also be noted that the function is exponential which creates the potential for very large penalty values. Deadhead and class continuity become the dominate factor when the route is within the ideal service time window or very close.

**Design Process**

Given the fact that CASPER was not production software and that the USGS DLG data that were being used as a base map had not been completely verified, it was thought that the design process would have to be conducted by a person that was very familiar with the prototype system, Indiana’s state road system, and the snow removal process. In other words, a unit foreman with no introduction to the software could not sit down with the system by himself and expect to be able to design routes. In the future when CASPER becomes production software and is well documented, any person who has at least been
introduced to the software and is familiar with the geography and snow plow routing will be able to use the system by him or her self.

Route design for the Crawfordsville District began on June 15, 1992. Crawfordsville was the proving and training ground for the design procedure that was employed for the rest of the state. After approximately a week of designing with unit foremen, subdistrict managers, a district representative, and a Purdue technical consultant it was decided that the route designing process for each unit would be done best with the session being conducted by a state-wide coordinator or CASPER expert. Joe Lewien of the Crawfordsville District assumed this role. Joe spent many hours working with CASPER and consulting with Purdue experts on system functionality and operating procedures. By utilizing a state-wide coordinator continuity could be maintained between subdistricts and districts. Joe brought a considerable amount of expertise with regard to actual snow removal procedures, existing routes, and the operation of CASPER to each route design session.

The route designing process was quite tedious given the source data and the prototypical nature of CASPER. A tentative schedule for when each subdistrict was to arrive at Purdue was developed. Before the subdistrict representatives arrived at Purdue to design routes a Purdue research assistant would attempt to take the USGS DLG quadrangle files and merge them into a coverage for each unit in the subdistrict. Once this task was completed Joe Lewien would sit down with each coverage and verify the boundaries, road class, number of lanes, direction restrictions, depot location, and any other characteristics pertinent to INDOT’s road network and the snow removal process. This entire process was known as data filtering and verification, and was a very time consuming task. Given time constraints, data errors, and software limitations this process was not always successful.

When each unit’s or subdistrict’s representatives arrived to design routes the first half of the day was usually spent explaining CASPER, why INDOT wanted to re-design their snow routes, and letting the local experts view and correct CASPER’s representation of their unit’s road network. The second half of the day was spent designing routes. An initial set of routes was created with CASPER’s grow routes function after a consensus was reached by the decision makers as to the number of routes that should be initially designed. At this point the users could evaluate this initial set of routes and choose to either improve them or throw them out and grow a new initial set of routes. The improvement procedure could be done by either using CASPER’s heuristic improvement algorithm or by using a CAD-like environment where the user could modify individual routes based on experience and local preferences to converge on a new set of improved routes.

After approximately two weeks of route designing for Crawfordsville the issue of the official state policy for level of service for each class of road verses what level of service INDOT has actually been providing arose. The state’s official statement of policy states that a Class 1 road will be serviced every hour, a Class 2 road will be serviced every two hours, and a Class 3 road will be serviced every three hours. In actual operations at least over the last few years the subdistricts and units in many cases have been able to create routes that provide service well under these target times or in other words they have been
in many cases been providing a better level of service, at least on paper, than the state claims it will provide. Given that CASPER’s route designing algorithms are driven by the goal of providing the state’s documented level of service across all roads, in some cases, the CASPER developed routes ended up providing a lower level of service for some road segments that had been receiving a higher level of service than the state’s policy claims that they should be receiving. This has been possible because many units have more trucks and personnel than is necessary to provide the minimum level of service.

CASPER’s penalty function as previously described is dominated by the target service time objective for each class of route. The function will assess an equally severe penalty value for routes that either exceed or are below the desired value. INDOT’s existing snow routes were evaluated by examining each unit’s recorded routes and electronically tabulating each route’s class, service time, deadhead mileage, and class continuity. These statistics were then fed into CASPER’s penalty function routine to determine penalty values for INDOT’s existing snow routes. The results of this analysis for each unit shows that even in the cases where a unit was providing a higher level of service prior to the CASPER design, that unit’s existing routes have a much higher penalty score. The higher score is because that set of routes is servicing the road network more often than INDOT’s stated policy requires.

The fact that in some cases the CASPER routes were actually providing an inferior, though adequate, level of service to some road segments was the users major point of contention with regard to the use of CASPER. The unit personnel are INDOT’s closest link to the communities that they serve and are the most sensitive to their communities needs. They view their trucks as valuable resources and would for the most part prefer to have more trucks to service their local areas. One of the goals for the use of CASPER is the efficient use of existing resources to service the state’s road network and consequently in some cases the CASPER routes would service a unit’s roads with fewer trucks than they currently use. The unit representatives were sometimes threatened and wary of “losing” trucks to service their roads.

The CASPER paradigm to snow route design did present the unit personnel with the opportunity for the first time to sit down in front of a digital representation of their road network and evaluate how they were servicing it. Most of the users did understand and appreciate the recommendations CASPER presented them with even if they did not agree with them completely. In the cases were a complete consensus could not be reached as to the new design of routes the unit personnel were asked to at least try the new routes for the upcoming snow season and then report back specifically what was wrong or unworkable about each route. In the worst case they could fall back on their old routes or work up fixes for the new ones. It was stressed that the routes that they had just designed with CASPER were by no means indelible or perfect. The routes would have to be field tested and would most likely require some form of modification following their first season of use.
Results

After designing routes for four months it was decided that it would be best to stop in September for the 1992-93 winter snow season. An attempt had been made to re-designed approximately half of the state’s snow routes up to that point and it was thought that the limited amount of resources available to the project would be better used in implementing an accounting system that would provide a means for evaluating the re-designed routes. Also, any new routes that would be designed that late in the year could not be implement-ed for the current season.

The results for the four districts where designs were attempted are summarized in Table 7. It should be noted that not every unit in each district was done. In the case of units found in urban areas an attempt was not even made because of data resolution/quality reasons and the fact that the CASPER prototype does not currently handle complicated interchanges and intersections. In other cases problems with the USGS DLG data files were found that could not be overcome in a reasonable time frame.

<table>
<thead>
<tr>
<th>District</th>
<th>Number of Units Designed For</th>
<th>Number of Routes Before CASPER</th>
<th>Number of Routes After CASPER</th>
<th>Deadhead Mileage Before CASPER</th>
<th>Deadhead Mileage After CASPER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawfordsville</td>
<td>16</td>
<td>144</td>
<td>131</td>
<td>1286</td>
<td>1322</td>
</tr>
<tr>
<td>LaPorte</td>
<td>13</td>
<td>113</td>
<td>99</td>
<td>1436</td>
<td>1039</td>
</tr>
<tr>
<td>FtWayne</td>
<td>13</td>
<td>116</td>
<td>108</td>
<td>1174</td>
<td>1271</td>
</tr>
<tr>
<td>Greenfield</td>
<td>8</td>
<td>57</td>
<td>58</td>
<td>454</td>
<td>533</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>50</strong></td>
<td><strong>430</strong></td>
<td><strong>396</strong></td>
<td><strong>4350</strong></td>
<td><strong>4165</strong></td>
</tr>
</tbody>
</table>

For the 50 units that routes were designed for a total of 34 routes were eliminated or a 7.9% reduction in the total number of routes. A 4.3% reduction in total deadhead mileage was found. Larry Goode of Maintenance Management has estimated that INDOT would save $66,620 in the first year and $140,597 over ten years for each route eliminated. This equates to a $2,265,068 savings in the first year and a $4,780,284 savings over ten years from the elimination of the 34 routes by the use of CASPER. When extrapolated state-wide this figure could easily exceed $10 million.

These are the preliminary results of using the CASPER prototype system. These routes require field testing and verification. It was anticipated that some units would require modifications to be made to their route sets and possibly even an entire re-design after the field testing. With the possibility of some units requiring an additional truck after re-design and others implementing new configurations the net increases in improved efficiency should remain about the same.
One of the intangible benefits of the CASPER software system is the computer-based design and decision support environment that it provides its users. As the unit and subdistrict personnel become more familiar with the system and have even had the opportunity to customize or affect changes on its design they will inevitably use it more often to do analysis, design, comparisons, and what if or hypothetical testing of ideas. They will view the system as a valuable tool to manage their limited resources and provide a better level of service to the public.

**INDOT Evaluation of Results**

Larry Goode of INDOT Maintenance Management put together the CASPER snow route evaluation procedure and forms. This procedure basically put in place a four step process by which each unit could provide feedback as to the usability and goodness of each route they had designed with CASPER. The goal of the process was to evaluate how effectively CASPER had designed routes by getting feedback from the snow plow driver level.

The first step of the process was to document each new route. After each unit completed its CASPER session color printouts were produced of the routes they had designed. These printouts were taken back to the subdistrict offices where they were used to create INDOT route documents or forms. INDOT documents each of its routes with a tabular and map representation form. The subdistrict and unit personnel were also asked to strictly adhere to each CASPER route with only one truck so that a true and accurate evaluation of the CASPER routes could be performed.

The second step in the procedure was to simply test the routes on a dry run basis and train the drivers. Each driver was to go out and drive his or her route in dry pavement conditions so that they could learn and become comfortable with it. They could also document any problems that they might foresee with the route at that time such as traversal time.

The third phase of the procedure was to formally document each traversal of each route during a snow event. A standard evaluation form was produced for this purpose. The form for each route consisted of spaces for the designed traversal time, the actual traversal time, the road condition, whether the truck was plowing or spreading on that pass, and remarks section for documenting problems or the lack thereof. Each driver filled out these forms for every pass they made of their respective routes and the subdistrict offices collected the forms.

The fourth and final part of the procedure was to synthesize the evaluation forms. If a route was found to be absolutely unusable then the subdistrict was to locally fix the problem in whatever way they deemed necessary. All other documented problems were to be sent to the state office for compilation. With this information the state could track and compile statistics on the effectiveness and usability of the CASPER routes.

The results for the 1992-93 snow season have been compiled for 262 routes (66% of the total number of routes re-designed) and 72% of the CASPER designed routes were found to be acceptable. The subdistrict acceptance rates varied greatly from 23 to 100%.
The reasons behind the large variance in acceptance have yet to be fully investigated at this point, but could be related to problems with the base data, the constant travel speeds that were assumed during the design, or minor problems that are being perceived as major. The 72% acceptance rate is very promising given this was a first run with prototype software and an imperfect base map and data.

The final part of the evaluation phase is to re-design or improve the 28% of the routes that the drivers found problems with. This process is currently under consideration by INDOT. This process could also help improve the CASPER software if a problem with a route is found to be caused be the underlying algorithms or settings in the system software. The feedback process can lead to better routes and a better system for designing and managing those routes.

A complete technical description of the CASPER prototype may be obtained by contacting:

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References


